ON THE PRODUCTION AND SEPARATION OF INDUSTRIALLY USEFUL ISOTOPES IN SPACE

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ABSTRACT

Preliminary work on a concept of an orbital facility for production and separation of industrially useful isotopes will be discussed. The production facility consists of a large solar powered electrical generator and a high current charged particle accelerator that produces isotopes by bombardment of a suitable target. Several possible methods for chemical or physical separation of the produced isotopes in space will be discussed. Emphasis will be placed on the production of plutonium or uranium-233 for use in terrestrial power reactors. Possible advantages of an orbital facility over a terrestrial one will be discussed.

Environments that are accessible in space and that have characteristics that are difficult or impossible to achieve on the earth can make possible new large-scale industrial processes that will directly benefit people living on earth. Among these characteristics are the following:

1. A state of weightlessness.
2. A vacuum that extends throughout an arbitrarily large volume.
3. The presence of the earth's magnetic field outside the earth's atmosphere.
4. Solar energy at intensities ranging from zero through 0.14 watts per square centimeter at the earth's orbit to approximately 7.0 kilowatts per square centimeter near the sun's surface.

5. Line-of-sight observational access to all of the earth's atmosphere and surface.

6. Access to raw materials, particularly on the moon and asteroids, the extraction of which will not affect the earth's natural environment.

7. Physical separation from the earth's biosphere.

For an industrial process in space to be worth developing, however, it should satisfy several conditions:

First, the total costs per unit mass of the product made in space, including all transportation costs to and from space, should be competitive with the cost of making the product by terrestrial means. In the case of products that are made from raw materials originally found on the earth, the value of the product must obviously be greater (in many cases, much greater) than the cost per unit mass of placing material in space and returning it to the earth at the time when large-scale production in space is anticipated.

Second, the expected market for the product should be large enough to justify the total anticipated costs of development and use of the space-based production facility.

Third, the "externalities" associated with the space production process should compare favorably with those associated with terrestrial production of the same product. Such externalities include the danger of major accidents, health hazards to the public and operating personnel, pollution of the earth's environment, aesthetically unpleasant (or pleasant) side effects, and spoilation (or conservation) of scarce raw materials.

Note that I have not insisted that the cost of a product be less if made in space than if made on earth, but only that the cost be "competitive." Insistence on lowest cost methods for production, such as have characterized much of modern industry, has often led, through pollution and other harmful side effects, to very high external costs to the general public. I am rapidly becoming convinced that perhaps the most important benefit to humanity to be found in large scale human activity in space will be through a gradual transfer of industrial processing and manufacturing, with all of their damaging effects on the earth's natural biological environment, to space. If, as now seems most likely, there is little or no biological activity on the moon or the asteroids, I would far rather have us do our massive scrapping, digging and boring for raw materials there, and throw our waste heat and poisonous chemicals and radioactive wastes into distant space or the sun, than to continue to foul this beautiful and delicately balanced planet that we live on.

If we should undertake a gradual transfer of industries to space, it seems reasonable to consider parts of the nuclear industry among the first. Some industrially useful radioisotopes, such as Californium 252, cost of the order of a billion dollars a gram or more! Plutonium for use in nuclear power reactors currently costs approximately $10,000 per kilogram, which is about an order of magnitude greater than the present costs of placing materials in earth orbit. The foreseeable worldwide market demand for plutonium is in the range of tens of thousands of kilograms per year within the next decade. The worldwide market demand for fabricated fuel elements containing plutonium or U-233 for power reactors is likely to be of the order of $100 billion per year by the end of this century. So these materials satisfy our requirement for high unit values and large expected markets.

Next I want to consider some of the possible advantages, other than material costs, of producing nuclear fuel materials in space. Although U-235 is the primary fuel in almost all power reactors in use or under construction, conversion to breeder reactors that convert the vastly more plentiful, naturally occurring, U-238 or thorium-232 to plutonium or U-233 is generally expected to start on a big scale during the 1980's.

In principle, all the foreseeable demands for plutonium of U-233 can be met by use of such breeder reactors. In practice, however, there are serious difficulties. Fast breeder reactor cores are inherently unsafe, and require considerable care, extensive engineered safeguards, and containment structures in order to assure that, under all credible circumstances, there can be no major release of radioactive products to the environment. Thermal breeders that use the thorium-U-233 breeding cycles are also under development, and there is some hope that the cores of such reactors can be made inherently safe against accidental loss of the capability either to cool the reactor or to shut down the reactor by insertion of control rods. In both types of reactors, however, the requirement that they produce more neutrons than are consumed to sustain a chain reaction imposes severe restrictions on the types of materials and design concepts that can be used. Furthermore, all breeder reactors now under development require extensive fuel reprocessing facilities to sustain an economic overall breeding fuel cycle. Such facilities produce huge volumes of radioactive wastes that must be contained and disposed of in ways that permanently assure that they will not flow into the natural environment.

If, however, natural uranium or thorium could first be converted to plutonium or U-233 by some means other than the use of breeder reactors, and supplied to the nuclear industry in fabricated fuel elements that, by use of suitable "burnable" poisons, could have sufficiently high fuel burnup efficiencies to avoid the need for breeding in power reactors or chemical reprocessing of fuel, the safety and radioactive waste disposal problems would be greatly alleviated. This possibility

would be economically attractive if the plutonium or U-233 could be supplied at a cost of about $10,000 per kilogram or less. This is the primary objective of the isotope production concept I shall briefly discuss.

Plutonium or U-233 can be produced by neutron capture in natural uranium or thorium. Neutrons for this purpose can be supplied in at least three ways: by fission in a reactor, by charged particle beams that produce neutrons in a suitable target, and by thermonuclear explosives. For reasons just given, I shall exclude the first.

Nuclear explosives are, by far, the cheapest sources of large numbers of neutrons that we have: a 10 Megaton thermonuclear explosion can be made to release enough neutrons to produce more than 5,000 kilograms of plutonium. The problem is to do this in such a way that the product can be contained and economically processed without seriously (or even catastrophically!) preturbing the environment. The plutonium can either be produced in the explosive device itself or by irradiation of a suitably placed and protected blanket that is not melted or vaporized by the explosion. Both concepts have been studied in some detail for use underground or on the earth's surface. We have recently done some preliminary thinking about the use of such techniques in space -- confining the explosions beneath the surface of the moon or, conceivably, a large asteroid, or irradiating blankets by sequential explosions in space. Partly because of the current ban on all nuclear explosions in space, however, we have concentrated more effort on a highly preliminary study of isotope production by the impact of beams of high energy charged particles on a suitable target in space. I shall therefore restrict the remainder of this discussion to that concept.

The concept consists of six primary components: A solar energy conversion source of electric power, a linear accelerator for producing a high energy beam of deuterons, a target within which the isotopes are produced, a facility for separating the isotopes after they have been made, a facility for fabrication of power reactor fuel elements, and supporting facilities required for operation of the system in space.

The spirit of this highly preliminary analysis has been to make all estimates on the optimistic side, to determine whether the concept can be definitely judged to be economically infeasible for the foreseeable future. As will be seen, we have concluded that the concept shows enough promise to warrant more detailed investigation, particularly if one is optimistic about prospects for sharp reductions in space transportation costs within the next several decades.

In order to review this concept in the context of large scale production operations in space, we have chosen values of the primary parameters that will appear very large to most people. If a concept such as this

were developed, it is clear that a development program would proceed through a large number of steps that would include many experiments and tests using much smaller components than those suggested in this paper.

We start from a premise that the production facility will produce 10,000 kilograms of plutonium or U^{233} per year, at a target cost of not more than $10,000 per kilogram, corresponding to a total annual production cost of the order of $100 million per year. This is comparable to the current total rate of consumption of special fissionable isotopes in power reactors in the United States today, and only a few percent of the expected worldwide consumption rate in 1985.

The plutonium or U^{233} is produced by capture of neutrons in U^{238} or Th^{232}. We propose that the neutrons be produced by the impact of approximately 200 MEV deuterons on a target that serves the triple purpose of yielding neutrons following deuteron impact, capturing the neutrons in fertile material, and radiating the deuteron and neutron capture energy into space. The deuteron accelerator is a linear accelerator of unspecified design that converts electrical energy, with high efficiency, to kinetic energy of the deuteron beam. The electric power source consists of a very large, spherically or parabolically surfaced solar energy collector that is used to concentrate the solar energy flux to produce sufficiently high temperatures for driving an electrical power generating system. Working backwards from the presumed plutonium production rate, we have derived the highly tentative production facility parameters shown in the following tables, using the indicated energy conversion efficiencies:

TABLE I

SOLAR ELECTRIC POWER SUPPLY

Electric power output	3,000 Megawatts
Total efficiency $\left(\frac{\text{electric power}}{\text{intercepted solar power}}\right)$	40%
Total intercepted solar energy	7,500 Megawatts
Area of solar energy reflector	5×10^{10} cm^2 (3.5 km^2)
Radius of solar energy reflector	1,100 meters
Thickness of aluminized milar reflector	10^{-3} cm = 10^{-3} g/cm^2
Mass of reflector material	5×10^4 kg
Mass of reflector supporting wires	5×10^4 kg
Maximum temperature of electric generator materials or working fluid	3000° K
Mass of electrical generators system (30 kw (e)/kg	10^5 kg

Table I, continued.

Average surface temperature of radiator	1300° K
Area of radiator (emissivity = 0.9) (14.3 watts/cm^2, 4,500 MW radiated power)	3.4×10^8 cm^2
Mass per unit area of radiator	.3 g/cm^2
Total mass of radiator	10^5 kg
Radius of radiator	110 meters
Total mass of power supply	3×10^5 kg
Total electric power/mass of power supply	10 kw/kg

TABLE II

DEUTERON LINEAR ACCELERATOR

Deuteron energy	200 MEV
Total beam power = electrical input	3,000 Megawatts
Beam current	15 amperes
Assumed length of accelerator	1,000 meters
Average electric field along accelerator	2,000 volts/cm
Assumed total weight of accelerator, including electric power conversion system, accelerating drift tubes, etc.	1.25×10^5 kg

TABLE III

TARGET AND BREEDING BLANKET

Assumed number of neutrons/incident deuteron	10
Power that must be dissipated by radiation from target (beam power plus neutron capture energy)	4,500 Megawatts
Assumed target surface temperature	2300° K
Area of target (σ = .8)	3.4×10^7 cm^2
Deuteron beam current density at target	4.5×10^{-7} amp/cm^2
Mass per unit area of target (U^{238} or Th^{232} + BeO + C)	20 g/cm^2

Table III, continued.

Mass of uranium or thorium in target (UC^2 or ThC^2)	5×10^4 kg
Total mass of target	6.8×10^5 kg
Total mass of plutonium or U^{233} produced per year	10,000 kg

TABLE IV

ISOTOPE SEPARATION
AND FUEL FABRICATION FACILITIES

Time between separations of Pu^{239}, Pu^{241}, U^{233}, U^{235} from uranium or thorium and fission products in blanket	1 year
Concentration of Pu or U in U^{238} or Th^{232} layers of blanket prior to separation	20%
Total mass of material to be separated	5×10^4 kg
Assumed total mass of isotope separation and fuel fabrication facilities	1.25×10^5 kg

TABLE V

SUPPORTING FACILITIES
REQUIRED FOR OPERATION OF SYSTEM

Assumed total mass of supporting facilities (manned space station, control equipment, auxiliary power supplies, life support equipment, station-keeping propulsion units, system assembly equipment, shops, etc.	5×10^5 kg
Assumed total annual mass that must be placed in orbit to supply facility with operating personnel, depleted supplies, and uranium or thorium	1.5×10^5 kg/yr

TABLE VI

SUMMARY OF
OVERALL SYSTEM PARAMETERS AND ECONOMICS

Total mass of facility	1.7×10^6 kg
Assumed useful life of facility, including non-nuclear materials for breeding blanket	20 years
Total operations supply mass placed in orbit @ 100,000 kg/yr	2×10^6 kg
Assumed cost per unit weight of transport to orbit and rendezvous with facility components	$200/kg
Total cost of placing facility and operations supply mass in orbit	$\$3.7 \times 10^8$
Total value of fissionable matter produced in 20 yr operation, @ $10,000/kg	$\$2 \times 10^9$
Total allowable cost of fabrication of all payloads, of ground support operations, and manual space operations to achieve "break even" point (Total value of fissionable material produced and recovered = total costs of 20 year operation)	$\$1.3 \times 10^9$

The parameters listed in the above table, though internally consistent, are first order estimates that are not based on a detailed analysis of a specific proposal for each component of the system. Since the entire concept is in the very early stages of conceptual design, I do not yet include any systematic description of the components. I have chosen, rather, to list the following qualitative points about some of the components.

1. Solar radiation pressure acting on the solar energy collector is apparently sufficient to maintain the shape of the collector mounted on a grid of thin, high strength wires, and to assure that the collector is directed toward the sun when it is not in the earth's shadow. A low power, high specific impulse propulsion system may be required to prevent the orbit from elongating. A stable configuration can be achieved by a parachute-like arrangement of the collector sheet, wires and appropriate masses.

2. A high temperature, closed cycle gas turbine appears to be an attractive method for converting the focused solar heat to rotational

kinetic energy. If a Brayton cycle engine is used, the working fluid (helium or argon, to have a high value of γ) can be cooled after the expansion part of the cycle by circulating it through a system of thin-walled radiator pipes before the compression part of the cycle. The peak temperature in the cycle is chosen to be as high as possible, to obtain a high efficiency, and to allow radiation of the waste heat at a high temperature. The expander, compressor, heating chamber, and radiator weights are based on a peak operating pressure of the order of 100 pounds per square inch. It is likely to be necessary to use superconductors to achieve the low weight per unit power assumed for the system to convert rotational kinetic energy to electrical energy. It is important to achieve a very high rotational velocity in both the engine and the generator, which can perhaps be combined in the same mechanical unit.

A variety of thermoelectric, thermionic, and magnetohydrodynamic conversion techniques may also be suitable, and perhaps require less mass per unit power output.

I realize that the electric power output per unit weight shown in Table I is several orders of magnitude greater than those now achievable with solar panel arrays. This is the combined result of using a very large, low mass collection and focussing system, very high surface temperatures for radiating waste heat, and the scaling benefits that come from using a very high power output system. We are currently studying the dynamics of such large collectors, when subjected to gravitational tidal forces, radiation pressure, and a variety of electromagnetic forces.

3. The deuteron accelerator should be designed from first principles, to assure that appropriate advantage is taken of the vacuum environment and state of weightlessness. If it saves mass, use should probably be made of superconductors. The thrust delivered by the deuteron beam is small -- of the order of a few kilograms -- and should therefore not produce significant tensions in the accelerator-target system.

4. The target should be sufficiently thick to stop the neutrons produced by the deuteron beam, requires moderating material to slow neutrons down to the resonance capture region, and must consist of materials that have a low vapor pressure at temperatures somewhat above the surface radiating temperature. We have, therefore, chosen uranium or thorium carbide, graphite, and beryllium oxide to make up the blanket. There is some optimum ratio of graphite to BeO that will minimize the total mass per unit area required for a given absorption probability per neutron. We believe that a thickness of $20 g/cm^2$ should guarantee capture of more than 75% of the neutrons, since the transport mean free path of several MEV neutrons in BeO is approximately 2.5 cm ($7.5 g/cm^2$). The UC_2 or ThC_2 would probably be distributed in thin sheets throughout the blanket, so that only they would have to be processed for isotope separation.

5. One of the likely reasons why this general type of isotope production facility may cost less to construct in space than on the earth's surface is the result of the requirement for an immense evacuated region to accommodate the deuteron beam and the accelerator's accelerating electrodes or drift tubes. For the values of the beam parameters we have chosen, the charged particle beam is likely to be several tens of meters in diameter, to maintain a stable beam. The very preliminary choice of a length of one kilometer was made to assure that there would not be problems of electron cascading between electrodes. The corresponding volume of the evacuated region is thus of the order of a million cubic meters which, though not necessarily completely beyond reason for a terrestrial vacuum, is orders of magnitude beyond any present experience. Further economic and technical analyses of this concept should obviously include comparisons between the costs of terrestrial and orbital facilities for producing the same product.

6. Several concepts for separation of the fissionable materials from the isotope production blanket come to mind, and each of these should be examined in some detail before even preliminary choices of a specific method can rationally be made. Among the methods that might be especially attractive for use in space are chemical separation techniques, gas centrifuge methods, and any of several methods for electromagnetic separation. The assumed facility weights shown in Table IV are simply preliminary goals. We have taken a cursory look at the possibility of electromagnetic separation of ion streams of the fissionable isotope-bearing part of the production blanket, using the earth's magnetic field. Space charge defocussing of the ion stream appears to be a problem, but several space charge neutralization techniques at least appear to warrant further study.

7. The estimated and postulated costs given in these tables do not allow for fabrication of finished reactor fuel elements in an orbital facility. It is assumed, rather, that the separated fissionable materials would be packaged and returned to earth for incorporation into fuel elements in terrestrial facilities. It is possible, however, that some of the fabrication and processing techniques that have been discussed at this symposium, as well as other techniques that make use of the unique environments available in space may make it attractive to fabricate the fuel elements in space. We propose to examine this possibility further.

8. Estimates of the required supporting facilities and operations in space and on the ground are all highly speculative, and not based on any specific analysis. If the concept should be developed for production of a significant fraction of the fissionable material consumed in the world's power reactors several decades from now, production rates are likely to be an order of magnitude or more larger than the 10,000 kilograms per year assumed for our example. In this case, the number of operating personnel in space could be several hundred, without raising the total unit cost of fissionable materials above $5-10,000 per kilogram.

I should like to close by listing a few types of orbital experiments that relate to this concept and that appear worthwhile if it is assumed that more detailed study of the concept than we have carried out so far should make it appear practical and economical.

1. Observation of the dynamics of large, thin membranes subjected to forces due to the earth's gravitational field gradient, radiation pressure from the reflection of solar energy, reaction forces due to the strength of the membrane and its supporting elements, and electromagnetic forces due to charging of the membrane and its interatction with the earth's magnetic field and charged particles in space. Note that such experiments are relevant to many possible applications of large space power systems that use large collectors to focus solar energy.

2. Tests of relatively small scale prototypes of solar power generators of the type I have been discussing. A prototype with an electrical output of approximately 100 kw would require a total mass of the order of 100 kilograms or less, and a collector with a radius of approximately 10 meters.

3. Studies of the electron emission of various configurations of conductors subjected to electric fields of the same order (several thousand volts per centimeter) as those envisioned near the accelerating electrodes of a charged particle accelerator.

4. Observation of the radiation emission rates and material evolution rates from surfaces of materials that are candidates for high temperature radiators, as functions of temperature (up to approximately 1000° C.), and in the space vacuum environment. The measurement of surface material evolution rates may be difficult to make realistically in ground-based vacuum simulation facilities of reasonable size.

5. Tests of scaled prototypes of ultra-high velocity gas centrifuge isotope separation systems that make use of the state of weightlessness.